Feasibility of HTS DC Cables on Board a Ship

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Feasibility of HTS DC Cables on Board a Ship

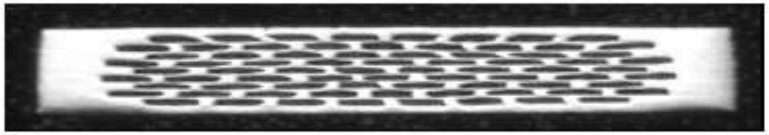
1. Can superconducting cables be used for DC distribution systems on board a ship?

2. Offers this solution any operational advantages over conventional resistive conductors?

Can superconducting cables be used for DC distribution systems on board a ship?

Superconducting Materials

1st Generation
Bi2223 tapes



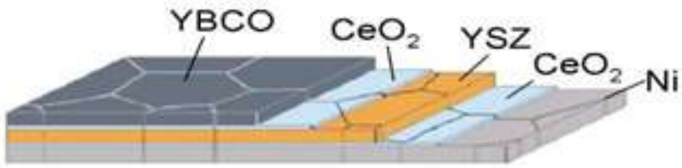
- Powder in tube process, HTS filaments are embedded in a silver matrix
- These materials can be cooled by liquid nitrogen (77 K), sub-cooled liquid
  nitrogen (65 K) or helium gas (10 - 80 K)

Typical data ....

• Dimensions:	4 × 0.25 mm
• Available Length:	up to 1 km
• Maximum Current:	160 - 200 A @ 77 K; sf
• Critical Temp.:	110 K (-163 °C)
• Price:	~25 $/m

Superconducting Materials

2nd Generation
YBCO coated conductor



- Superconductor material is deposited on a Ni-alloy
- YBCO can be cooled by liquid nitrogen (77 K), sub-cooled liquid nitrogen (65 K) or helium gas (10-80 K)

Typical data ……………………………………………..

- Dimensions: 4 × 0.1 - 0.45 mm
- Available Length: up to 1 km
- Maximum Current: 100 A @ 77 K; sf
- Critical Temp.: 92 K (-181 °C)
- Price: ~33 $/m

Superconducting Materials

2nd Generation
MgB_2 wires

- Powder in tube process
- Performance/cost ratio makes it attractive for high current DC cables
- Needs to be cooled down to 20 - 30 K (helium gas)

Typical data ……………………………………………………...

- Dimensions: 1 mm²
- Available Length: up to 5 km
- Maximum Current: 1000 A at 20 K; sf
- Critical Temp. 39 K (-234 °C)
- Price: 2-4 $/m

Cable Designs

General design of a HTS cable

1. A former on which the HTS tapes or wires are stranded around
2. For electrical insulation a dielectric is lapped around the HTS materials
3. A second HTS layer on the dielectric acts as a shield or current return

Cable Designs

Several cable principles can be used to distribute power on board a ship:

1. One phase cable
2. Bipolar coaxial cable
3. Twisted cable

Cable Designs

One phase cable
(HTS tapes)

- One or more layers of HTS tapes are stranded around the former; the dielectric insulates this layers
- For a DC cable system two of this cables are necessary
- It is possible to have both phases in one cable cryostat
- The return flow of the coolant can be integrated in each phase or one phase is the inflow, one the outflow
- One cable can be connected to the generator with the rated voltage and the other cable is the current return and it is grounded (0 V / +1000 V) or voltage is applied to both cables (-500 V / +500 V)

Cable Designs

Bipolar coaxial cable (HTS tapes)

- The most compact design
- The current return is in the same cable
- The current flows in one cable from the generator to the motor and back; no additional transfer line is needed
- Magnetic fields caused by both phases are superimposed; there is no magnetic field outside the cable
- The cable can be operated symmetrically (-500 V / +500 V) or with the outer HTS layer grounded (0 V/1000 V)

Cable Designs

Bipolar coaxial cable (MgB$_2$ wire)

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Cable Designs

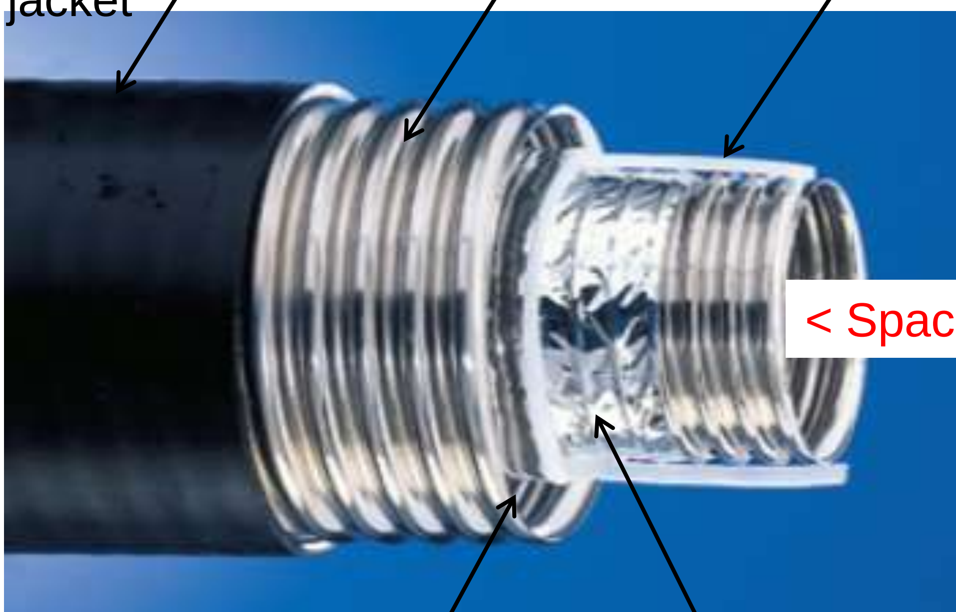
Twisted cable
(MgB_2 wire)

- The current return is in the same cable system
- The current flows in one cable from the generator to the motor and back
- The coolant return is integrated in the cable cryostat
- The magnetic field outside is minimized
- The cable can be operated symmetrically (e.g. -500 V / +500 V) or with the outer HTS layer grounded (0 V/1000 V)

Cryogenic Envelope

For operation the cable core has to be kept on its working temperature

2-wall cable cryostat (77 K):

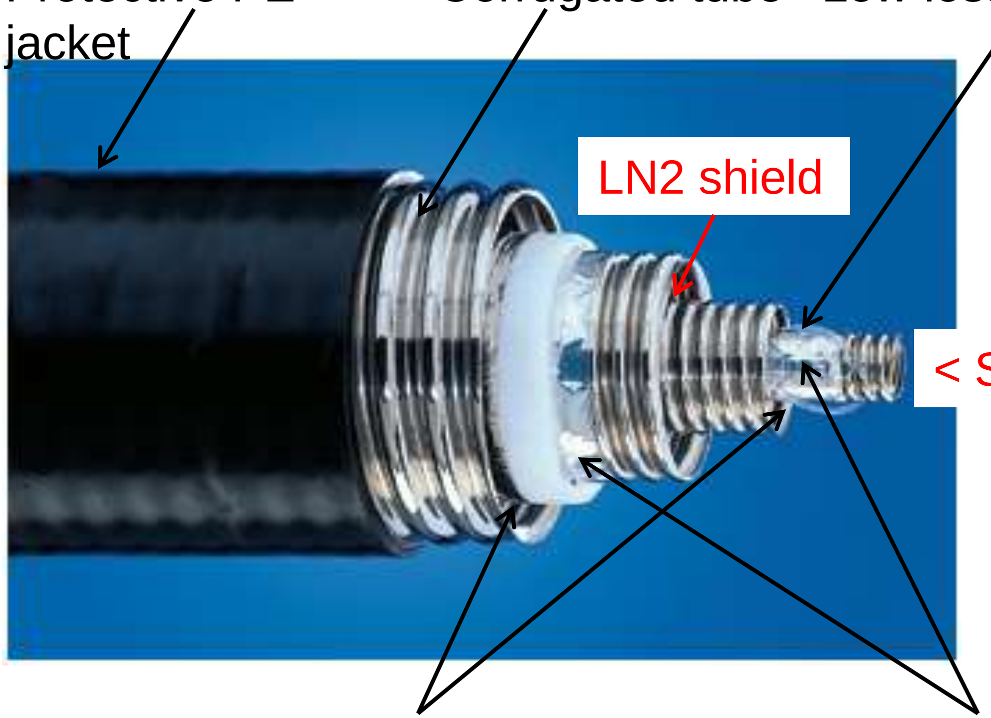


Cryogenic Envelope

For operation the cable core has to be kept on its working temperature

4-wall cable cryostat (20 K):

with LN2 shielding



Cryogenic Envelope

Cable cryostat, thermal losses

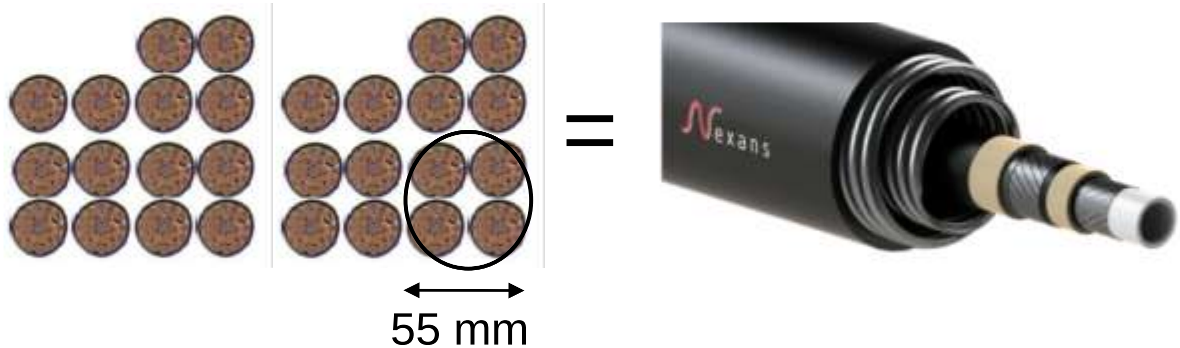
- Spacers, superinsulation & vacuum secure low thermal losses
- But still a remaining heat flow
  (Surface of corrugated tubes, thermal conductivity of spacers, vacuum quality, temperature difference)
- Different designs are possible
  (Specification of cable system, available space, price of cable cryostat)
- If higher thermal losses are tolerable
  $\Rightarrow$ Compact cable cryostat, but more powerful cooling system needed
- Typical 1 W/m,
  Possibility to reduce to 0.3 W/m

Cable Designs

Typical weight and the overall dimension for a 5 kA superconducting system

100 m MgB_2 coaxial cable with 5 kA @ 25 K	
Diameter of cable core	14.5 mm
Dimensions of cryostat	d_{in} 30 mm, d_{out} 58 mm
Weight of cable	35 + 130 kg
Volume of coolant	40 liter (He @ 25 bar)
Initial cool down time	< 2 days
Cable + cryostat losses	~50 W at 25 K

Copper: ~20 kg/kA/m $\Rightarrow$ 10 tons for 5 kA 100 m Copper system



Terminations (overview)

- The termination represents the connection of the cable end to the electrical devices
- An external cooling system is connected to the termination or a cooling system can be integrated in one termination
- Its design minimize the heat load on the cryogenic machine
- Its dimensions can be adapted to application and room available for an installation on board a ship
- For our cable system two bipolar terminations are required (bipolar = two current leads in a cryostat)

Current Leads

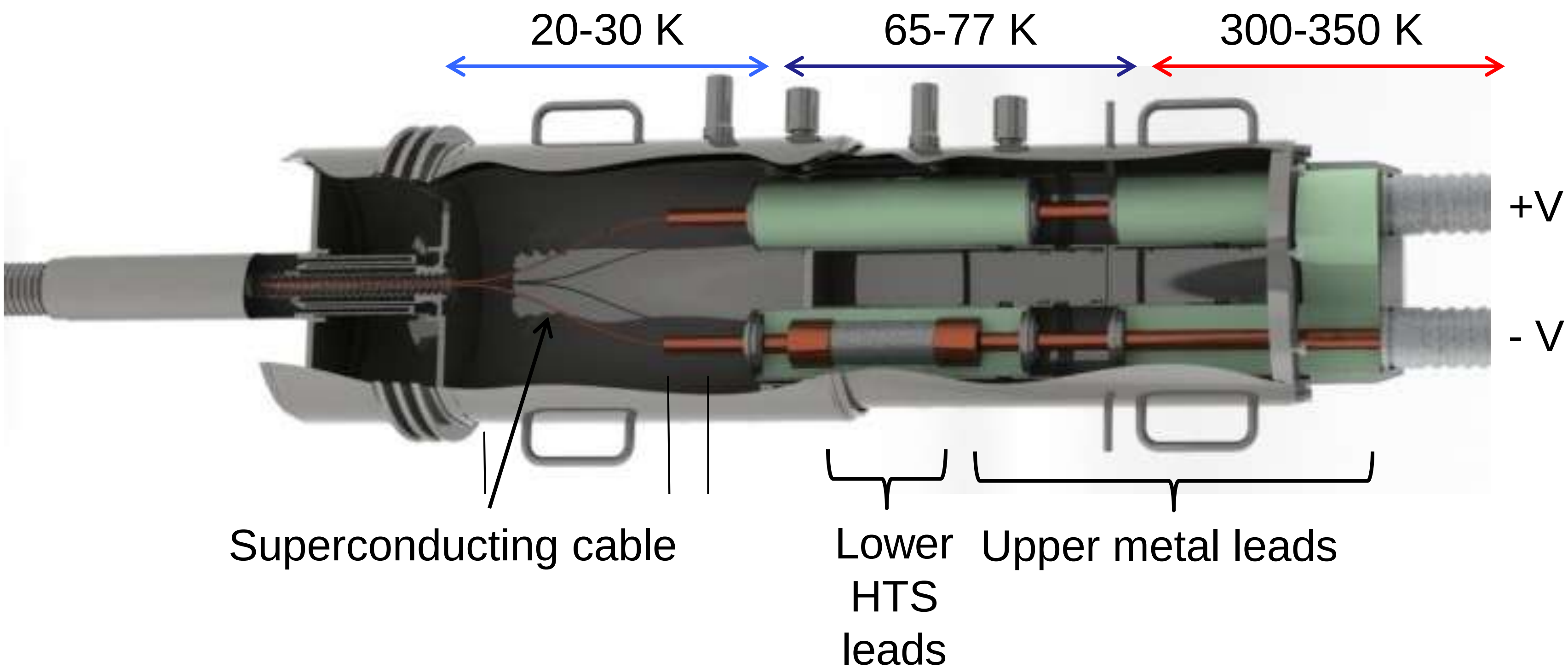
- Current leads generate most of the thermal and electrical losses
- Current leads should insure the following main specifications:

- Carry the current specified for the system without important Joule losses
  to avoid heat losses to the cryogenic media

- Limit the heat flux from ambient temperature (connection to motor / generator) to cryogenic temperature

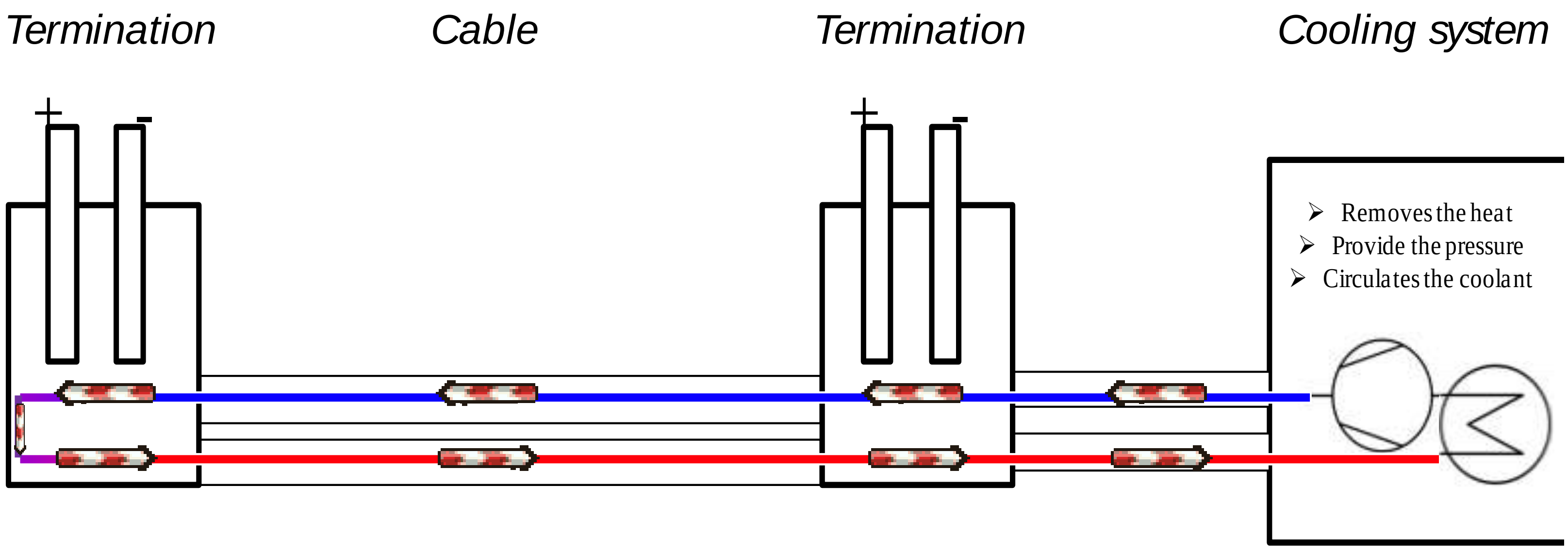
- Insure that cold flux from the part connected to the cryogenic area will not create a too low temperature (can create ice at the extremity connected to the motor / generator)

Sketch of termination design (20 K)



Schematic of the cooling system

- Cooling system is required to cool down the superconductor



Cooling System

Cooling system (Liquid Nitrogen)

- For Bi2223/YBCO, the temperature is below 100 K and can be achieved using **liquid nitrogen at 65 - 77 K**
- Liquid nitrogen is low price easy available and ideal for a fast cool down of a HTS cable system (high thermal capacitance)

Cooling System

Cooling system (Helium gas)

- Coolant for MgB_2: **Helium gas**
- Helium allows a wider range of temperatures down to **20 - 30 K**
- The operation at a lower temperature increases the ampacity
- When a lower operating temperature is used, the cryogenic system needs a higher cooling power

Cooling System

Volume of the coolant in cable: ~0.4 l/m

(depending on the rated current and the voltage level)

Total coolant volume:

100 m cable: 40 liter
+ Termination: ~100 liter
= 140 liter

Cooling System

Pressure drop / Temperature gradient

for three different cable designs, 100 m cable length

Design	Mass Flow	dT	dP
Coaxial, He @20 K	7.9 g/s	1.07 K	2.34 bar
Twisted, He @20 K	8.5 g/s	0.99 K	2.06 bar
Coaxial, N2 @65 K	34.8 g/s	0.77 K	1.56 bar

Cooling System

Promising cooling solution @ 65 K

Gifford Mac-Mahon
Cryomech AL 600 cold head
Cooling power: 510 W @ 70 K
Input power: 13 kW

Promising cooling solution @ 20 K
(2-stage system)

Stirling
Stirling Cryogenics SPC-4T
Cooling power: 220 W @ 20 K
Input power: 45 kW

Summary

Interim conclusion

Can superconducting cables be used for DC distribution systems on board a ship? **Yes (of course)!**

Benefits HTS

- Very compact cable
- Reduction of weight
- No thermal or electromagnetic impact on the environment

Drawback HTS

- Cooling system / low operating temperature

Offers a superconducting DC distribution system on board a ship any operational advantages over conventional resistive conductors?

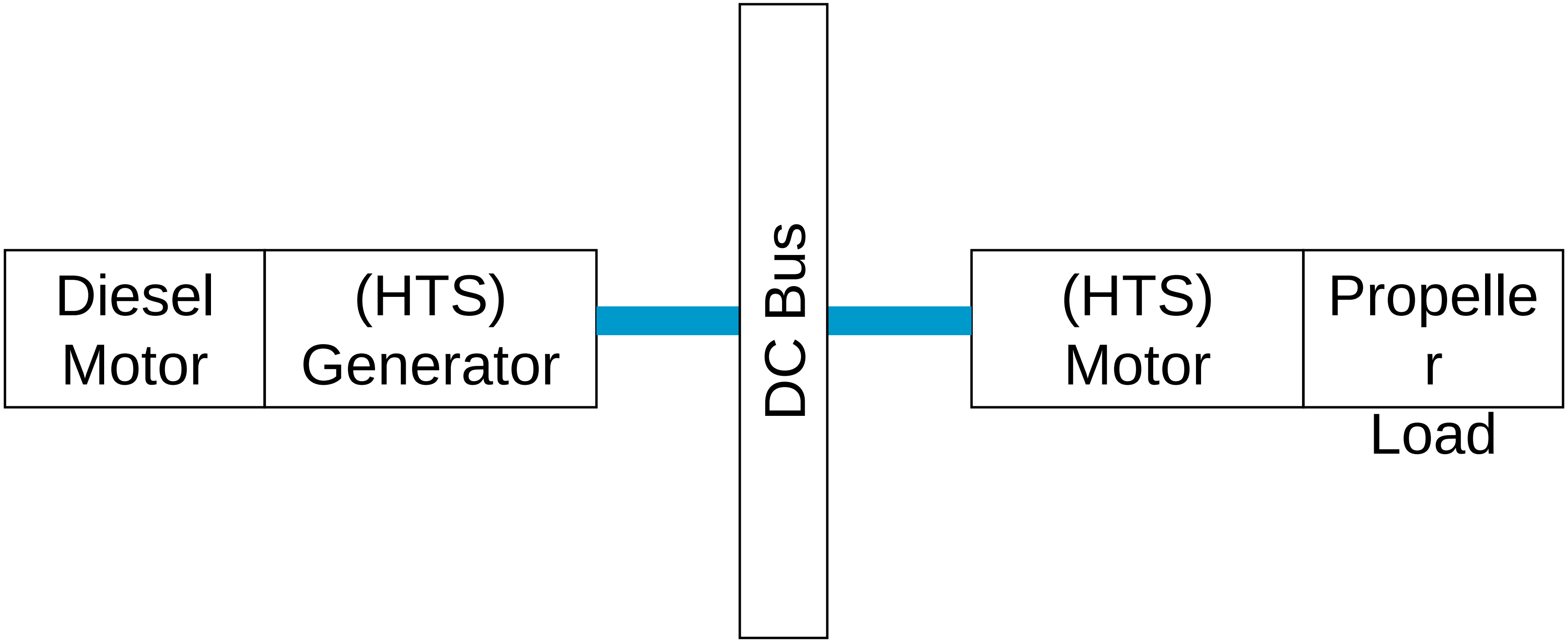
Power Distribution System

Overview

- Power distribution systems (AC or DC) can operate from low voltage (24 V)
  to medium voltage (15 kV) with various ampacity from 50 - 5000 A.
- Main advantage of a DC system operating at low voltage:
  No transformer or converter is required in the overall distribution system.
- The length of most distribution systems: 30 - 200 m
  (300 m for huge cruise ships, LNG tankers, container carriers)
- Ampacity of conventional resistive cables is limited on maximum operational temperature of 85 °C (ambient temperature of 45 °C).

Power Distribution System

- Replacement of high power cables between the generator and the bus-bar
  or between the bus-bar and the motor:



Power Distribution System

General assumptions for calculation of power losses and comparison of conventional resistive and superconducting systems:

Bipolar distribution system
1 - 10 MW, **<1000 V DC**

DC cable current
1 - 7.5 kA

Length
50 - 300 m

Ampacity of conventional resistive cable systems
1- 3 A/mm²

Power Dissipation Sources

Power dissipation sources

- Heat leak through the cryostat
- Thermal conduction / dissipation through the current leads
- AC ripples

Total losses of the system
when the cable is energized:

$$W_{Total} = 2 \cdot W_{Term} + L \cdot (W_{Cryo} + W_{ACRipple})$$

L: Length of cable

- Heat leak from cryostat independent from rated current
- Termination losses are mostly dependant on rated current
- AC ripple losses are dependent on frequency of ripples, rated current and amplitude of ripples

AC Ripple Power Dissipation

Voltage AC Ripples

$$W_{VACRipple} = 2\pi \cdot f \cdot \tan(\delta) \cdot C \cdot \Delta U^2$$

f	Frequency, max. 10 kHz
C	Capacity of the cable per meter in, max 0.4 nF
ΔU	½ Variation of the operating voltage = 8% of the nominal voltage 1000 V $\Rightarrow \Delta U = 40$ V
δ	Loss angle from the insulation material, 0.002° (Kapton)

$\Rightarrow W_{VACRipple}$ **< 0.3 mW/m**

$\Rightarrow$ Neglible!

AC Ripple Power Dissipation

Current AC Ripples

The AC current amplitude is limited to 3% of the nominal DC current with a maximum total harmonic distortion THD = 8%

$W_{IACRipple} = \mu_0 \cdot f \cdot I_c^2 \cdot f(i) / \pi$ (Norris formula)

$f(i) = (1-i) \cdot \ln(1-i) + (2-i) \cdot i/2$ *(Shape factor, elliptical)*

$i = \Delta i / 2I_c$ *(Δi: full amplitude of ripple in [A])*

The operating current of the superconducting cable is 70% of I_c

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AC Ripple Power Dissipation

Current AC Ripple losses for a typical harmonic spectrum

Cable class	1440 Hz	2880 Hz	5760 Hz	7200 Hz	Total
1 kA	0.0002	0.0005	0.0011	0.0013	< 0.0035
2 kA	0.0009	0.0018	0.0036	0.0045	< 0.011
3 kA	0.0021	0.0043	0.0087	0.0109	< 0.027
4 kA	0.0036	0.0072	0.0145	0.0182	**< 0.045**
5 kA	0.0059	0.0118	0.0237	0.0296	**< 0.071**
7.5 kA	0.0128	0.0256	0.0512	0.0641	**< 0.16**

- Negligible for an operating current below 3 kA (less than 10% of the 0.3 W/m cryostat losses)
- For higher currents the impact of the AC ripple are considered in the thermal analysis

Power Dissipation of Components

Power dissipation of the main components at the operating temperature

	Temperature	1 kA	2 kA	3 kA	4 kA	5 kA	7.5 kA
Current Leads (W)	77 - 90 K	99	192	287	384	482	739
	20 - 30 K	2.3	2.7	3.3	4.1	5.2	8.7
Cable Cryo (W/m)	65 - 70 K	0.3	0.3	0.4	0.5	0.5	0.5
	20 - 30 K	0.3	0.3	0.4	0.4	0.4	0.4
AC Ripple (W/m)	Operation temperature	0	0	0	0.05	0.07	0.16

- Most of the heat is coming from the “upper part” of the current leads
  $\Rightarrow$ High heat load on the cryogenic refrigerator

To be efficient, the superconducting cable system should not be too short!

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Power Dissipation of Components

Power efficiency of the cryogenic refrigerators*
[W at room temp. / W at operating temp.]
used for the calculations

Temperature	Carnot cycle	30 - 200 W	200 - 500 W	500 -1000 W
65-90 K	3.45	31	28	20
30 K	7.5	96	NA	NA
20 K	15	190	NA	NA

* Values from commercial systems available today.
The efficiencies of the cooling machines are in the range of 8 - 17% of the Carnot Cycle

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Comparison of Cu & SC System

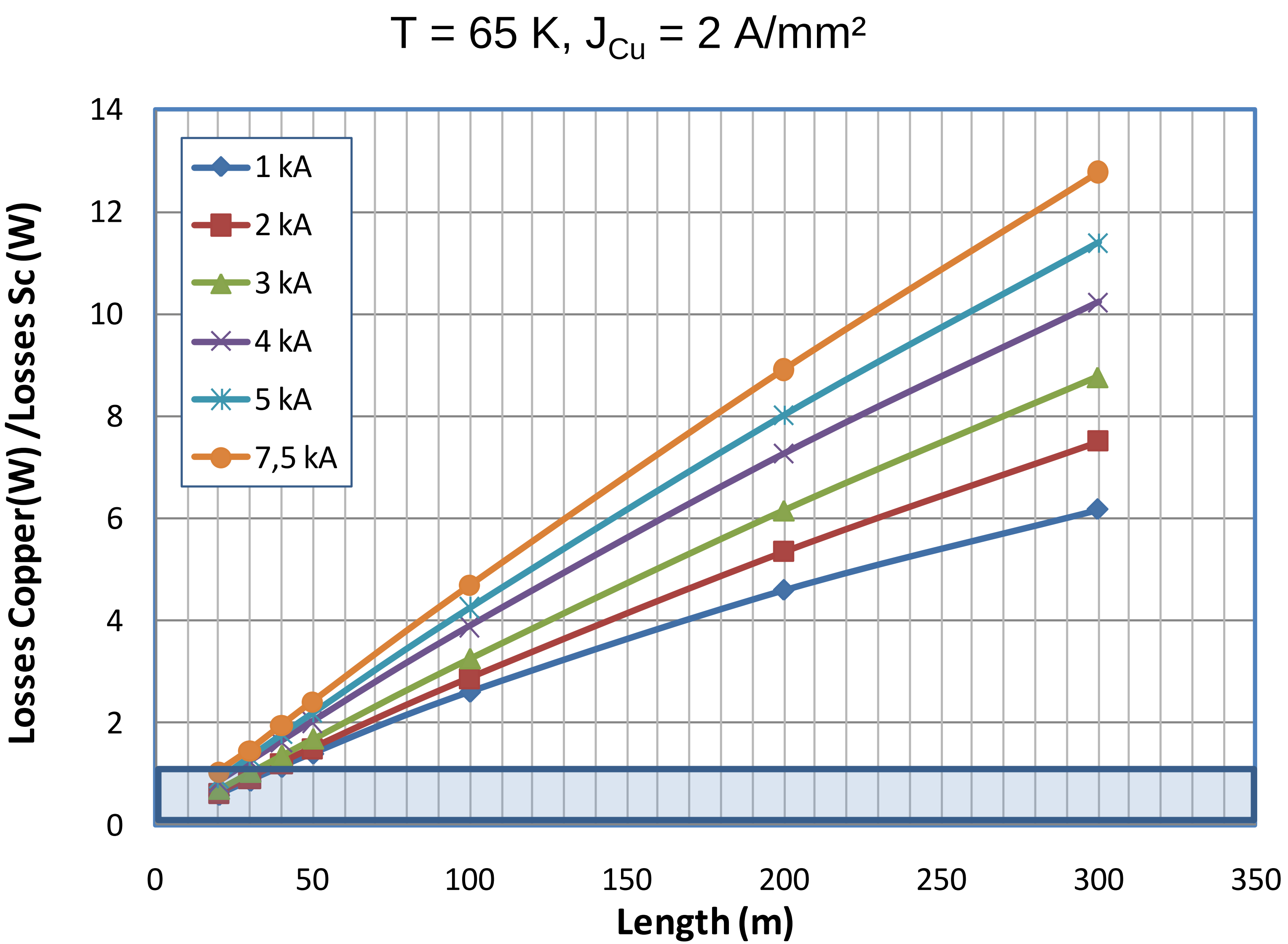
- The losses of superconducting system are compared with losses of conventional resistive system
- Copper cables have same length, operate at same ampacity
- Current density in the copper system is 1-3 A/mm²
- Losses copper system (single phase):

23	W/kA/m	1 A/mm²
92	W/kA/m	2 A/mm²
210	W/kA/m	3 A/mm²

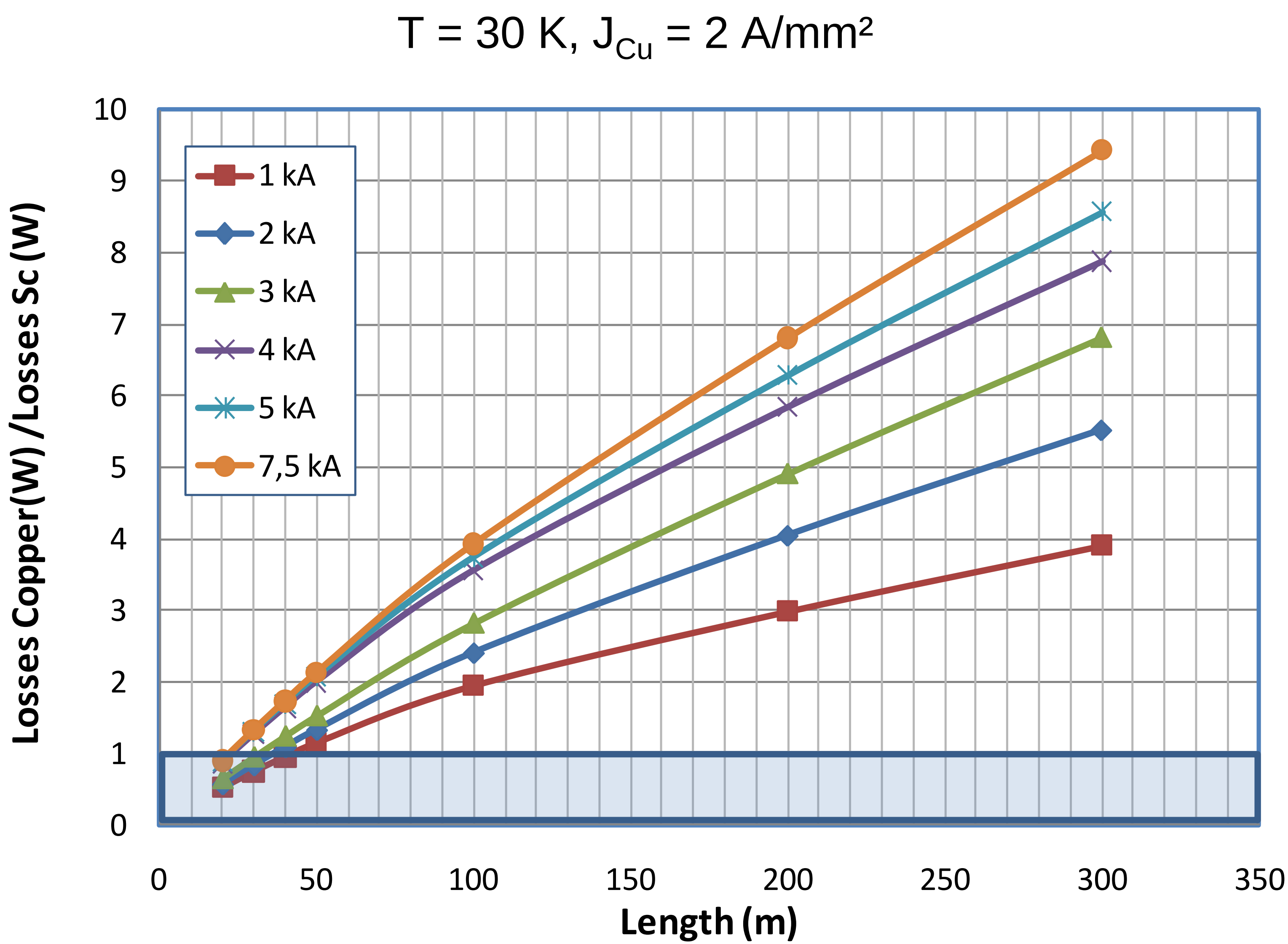
Figure of merit

- Ratio losses copper system / losses superconducting system
- Superconducting system is more efficient when this ratio is above 1

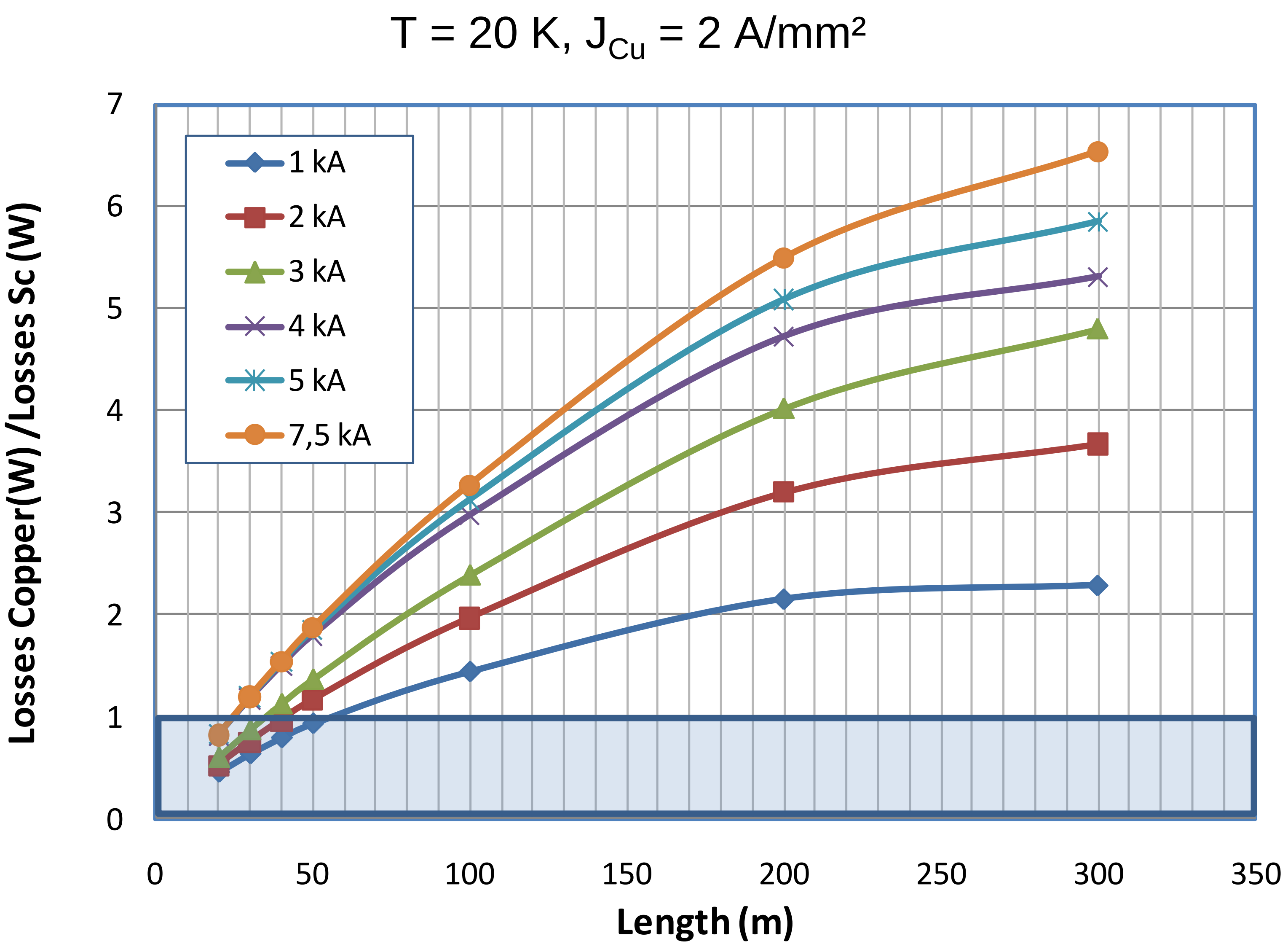
Comparison of Cu & SC System



Comparison of Cu & SC System

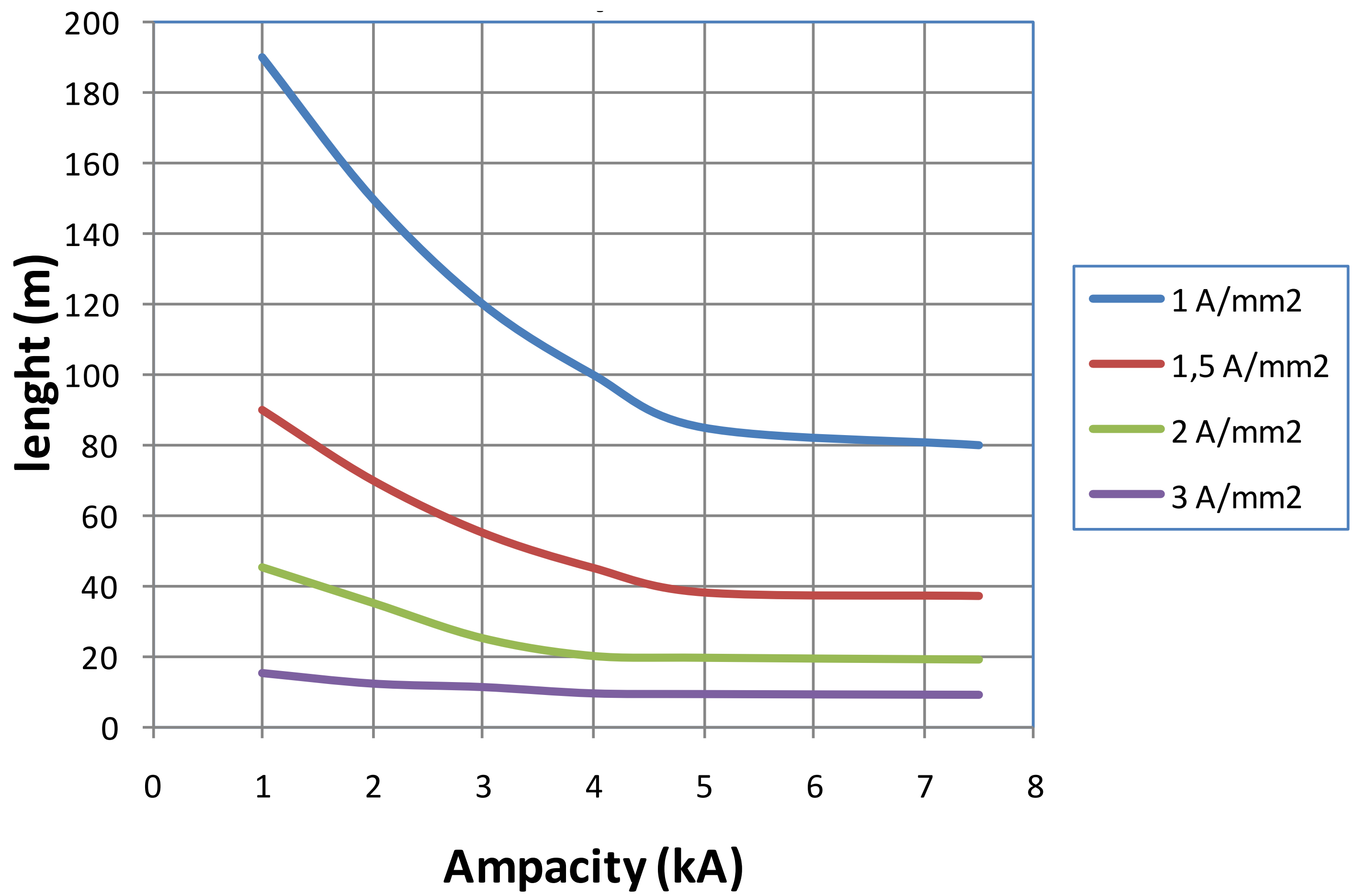


Comparison of Cu & SC System



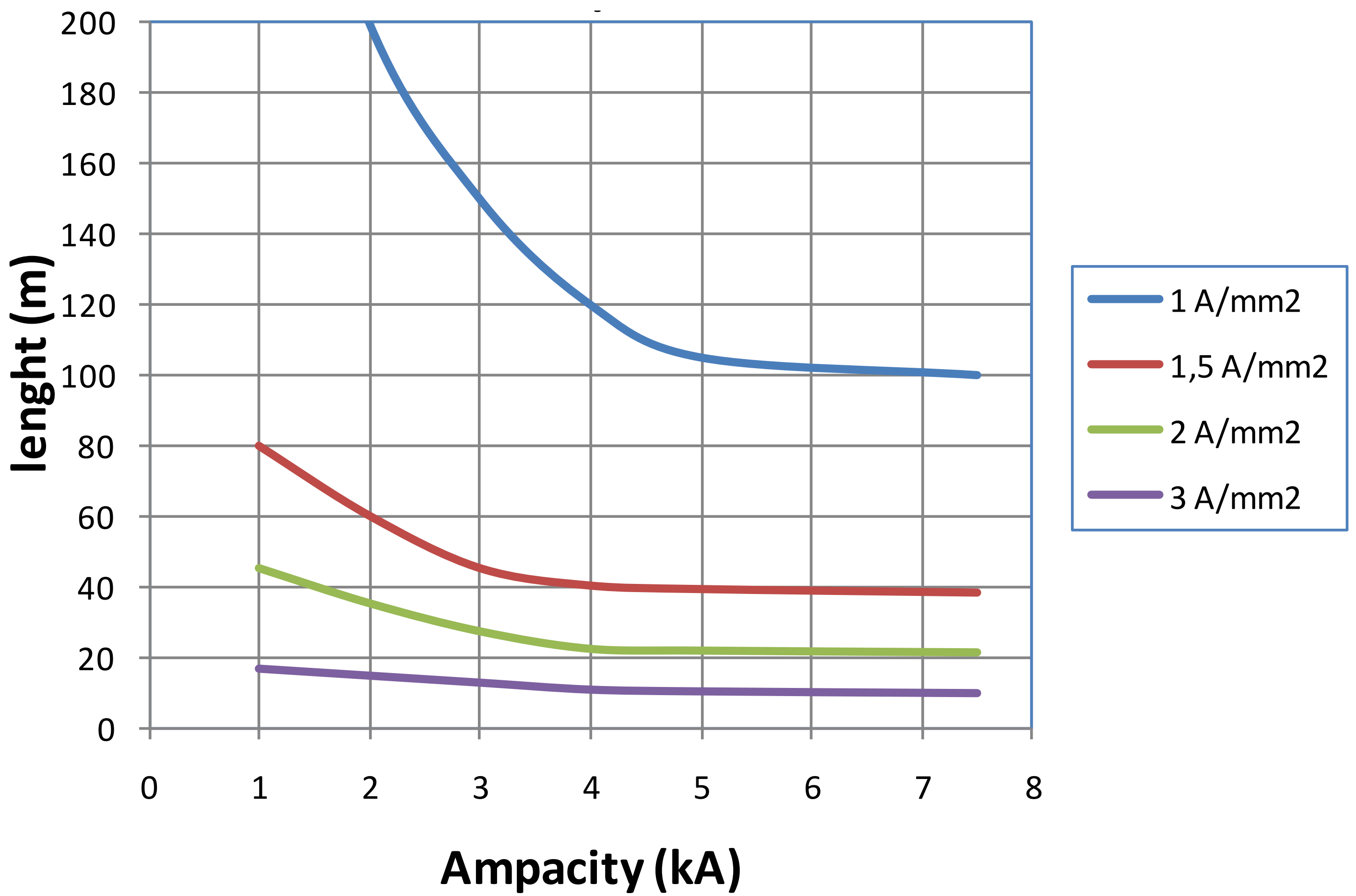
Comparison of Cu & SC System

Minimum length for SC, T = 65 K

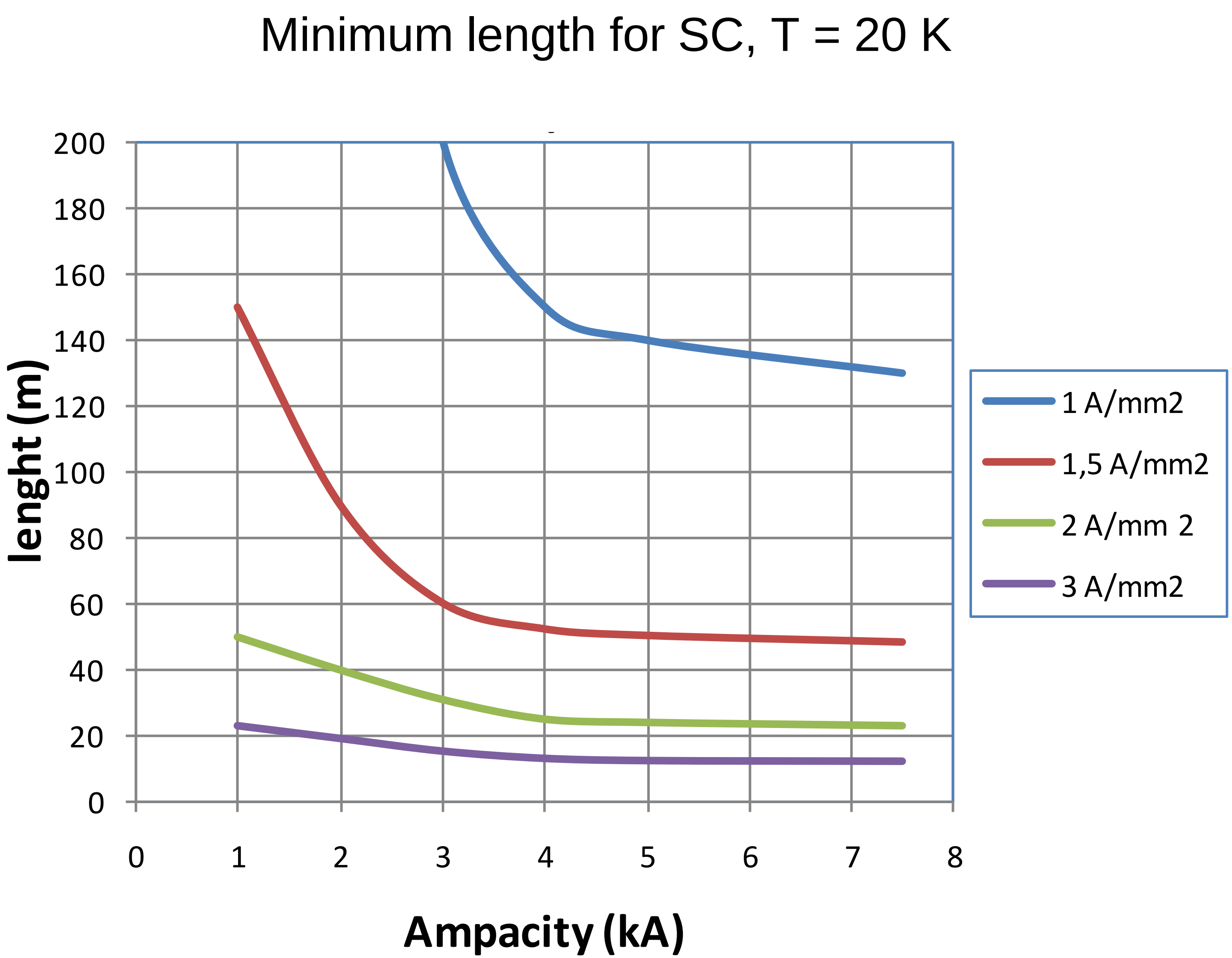


Comparison of Cu & SC System

Minimum length for SC, T = 30 K



Comparison of Cu & SC System



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Comparison of Cu & SC System

1. A “short” superconducting distribution system with a length of 50 m can efficiently replace a copper system especially when the space on board a ship is limited
2. A reduction of the losses up to a factor of 15 can be obtained with a superconducting system
3. The efficiency of the superconducting system is increasing with the distributed current and with the operating temperature
4. A system operating at 20 - 30 K with MgB_2 can be more efficient than a conventional copper system

Energy Saving

Overall losses in kW in a 100 m long distribution system (losses % of the transported energy)

Temp.	1 MW (1 kA,1 kV)	2 MW (2 kA,1 kV)	3 MW (3 kA,1 kV)	4 MW (4 kA,1 kV)	5 MW (5 kA,1 kV)	7.5 MW (7.5kA,1kV)
20 K	13 *(1.3 %)*	19 *(0.95%)*	23 *(0.77%)*	24 *(0.6%)*	30 *(0.56%)*	39 *(0.52%)*
30 K	9 *(0.9 %)*	15 *(0.75%)*	20 *(0.75%)*	21 *(0.48%)*	23 *(0.46%)*	33 *(0.45%)*
65 K	7 *(0.7%)*	13 *(0.65%)*	17 *(0.57%)*	18 *(0.45%)*	19 *(0.39%)*	29 *(0.39%)*
Ref Copper 1.5 A/mm^2 356 K	10 *(1%)*	20 *(1%)*	30 *(1%)*	40 *(1%)*	50 *(1%)*	75 *(1%)*
MVDC 10 kV	50 (5%)	100 (5%)	150 (5%)	200 (5%)	250 (5%)	375 (5%)

Sources of losses for MVDC: Transformers with 97.5% efficiency

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Energy Saving

1. In high current DC cables high energy can be transported at low voltage with a very high efficiency (losses <1%)
2. Such a system does not require medium voltage trans-formers or converters where 2 - 5% of the energy is lost
3. A 100 m long, 5 MW superconducting power distribution system in operation during 300 days per year can save:

   - 150 - 250 MWh per year in comparison with a conventional DC system
   - 1.5 GWh per year in comparison with a conventional MVAC (AC 10 kV - 500 A_{rms}) system
4. It contribute to recover the investments required for a superconducting system

Conclusion

1. HTS cables systems can have various designs; compared to copper cable, all designs are very compact and very light
2. Thermal and magnetic independency allows optimized installation possibilities
3. Due to low losses of HTS cable systems these are viable for length of more than 30 -100 m, depending on the rated current and the operating temperature
4. Power transmission architecture on board a ship can be realized at low voltage levels with high currents
5. Transmission architecture for classical cable (MVAC) needs converters and transformers to reduce the losses

Outlook

Beside the use as a power transmission cable on board a ship, other applications are imaginable:

1. Navy ships can be equipped with HTS degaussing cables (to neutralize the magnetic signature of the ship); a first HTS degaussing was tested 2009 by the US Navy on the destroyer USS Higgins
2. High power DC cable systems can replace several transmission systems at land; every application, where DC currents are required, can be operated by a HTS cable

Thank you
for your attention!